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DOE/PE/70549--T1

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DE86 007308

Characterization of Leaded Fuel Needs and Use

Topical Report for

Task 2 of IAG DE-AI01-84PE70549

Reported by

The Environmental Protection Agency

to

The Department of Energy

February, 1985

MASTER

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Introduction

This topical report is structured around the Statement-of-Work for the DOE/EPA IAG. This includes a discussion of the users of leaded fuel, valve recession and octane, alternatives to leaded fuel and geographical distribution of leaded fuel sales.

Section 2.1: Leaded Fuel Users

An initial estimate of those vehicles and equipment which are designed for leaded fuel use has been made for the Eleventh Periodical Report.[1] (Numbers in brackets refer to references listed at the end of the text.) Those estimates are not replaced by what is presented in this section of this report, but the information presented here can be used to refine and modify the estimates in [1] if that is considered necessary.

A note on syntax is appropriate here. The section is entitled "Leaded Fuel Users" and the Statement-of-Work indicates that this is to apply to vehicles and equipment that are designed for leaded gasoline. Actually for cars, leaded fuel users are greater in number than those cars designed for leaded fuel, due to the inappropriate use of leaded gasoline in cars designed for unleaded fuel.

Keeping in mind what will be needed for future sections, we can define ways to characterize any vehicle or equipment class that uses gasoline. These are shown below.

Table 1

Categorization of Fuel Users

	Uses Leaded Fuel	Uses Unleaded Fuel
Designed for Leaded Fuel	Design Use	Fuel Switching
Designed for Unleaded Fuel	Misfueling	Design Use

For this section, what is needed is emphasis on the vehicles and engines which were designed for operation on leaded fuel. Tables which give current and projected future fuel consumed in each category in Table 1 can be found in Reference 1 for highway vehicles. References 1 and 2 give a summary of what current estimates are for cars and trucks. Emphasis on the less well-understood classes is provided in this section.

The important fuel-consuming sectors are:

1. Motorcycles;

2. Off-highway equipment and vehicles:

   - Agricultural equipment;
   - Marine engines; and
   - Construction equipment.

In 1983, there were 6,960,000 motorcycles in the U.S.[3] Using the values listed in Reference 3, we have the following information:

Engine Displacement	Percent of Motorcycles	Road MPG
Under 125 cc	20.5	93
125-349 cc	28.8	80
300-449 cc	11.1	58
450-749 cc	16.7	48
749 cc	22.9	39

The road MPG is the MPG value reported in Reference 3. Since the value is claimed to be based on only the emission test (city) value (no highway test) and the city value for fuel economy is close to the overall road number, no adjustments were factored in to lower the city estimate.

The fleet average motorcycle MPG is therefore 58.6 MPG. Using the same base MPG for all types of motorcycles and reducing the MPG by 30 percent for off-road use, we have the following:

	Type of Motorcycle		
Miles Traveled (MPG)	On-Highway	Off-Highway	Dual Purpose
On-Highway	2729 (58.6)	--	908 (58.6)
Off-Highway	311 (41.0)	594 (41.0)	446 (41.0)

This yields the following value for gallons per vehicle per year:

Motorcycle Type	Gallons Per Motorcycle Per Year	Number	Total Gallons
On-Highway	54.2	3,700,000	200,540,000
Off-Highway	14.5	1,983,000	28,753,500
Dual Purpose	26.4	1,227,000	37,392,800
Fleet	37.6*	6,960,000	261,686,300

* Dividing total gallons by 6,960,000.

The total can be said to be roughly 0.3 billion gallons per year.

It is safe to assume that effectively all motorcycle fuel is purchased through retail outlets by the tankful. The Statement-of-Work calls for an estimate of the fuel used by rural/urban geographic splits, but to differentiate motorcycles from cars isn't necessary, for two reasons. First, the total fuel used, 0.3 billion gallons per year, is a small fraction of overall gasoline consumption which is estimated in Reference 1 to be about 92 billion gallons for 1985. Second, the rural/urban VMT split for motorcycles is not that much diffeerent for passenger cars. In Reference 3 we find:

Riding Average	Percent Annual Mileage	
	On-Highway	Off-Highway
In major cities	27	8
In suburban areas	35	17
In rural areas	48	79

Since on-highway motorcycles are the more important, and the 52/48 split is almost the same as the 55/45 value commonly used for passenger cars, no special mention of urban/rural split is needed.

In order to estimate the amount of unleaded fuel consumed by motorcycles, the total number of gallons was apportioned by the assumption that twice the motorcycle population of California used unleaded gasoline and this value (1,665,000) was divided by 6,960,000 and the resulting ratio, 0.24, was used with the total of 261,686,300 to yield 62,624,000 gallons.

Therefore, roughly speaking, out of the 262 million gallons of gasoline consumed by motorcycles, 62 million is unleaded gasoline, leaving a leaded fuel consumption of 200 million gallons per year.

No information on fuel octane or valve recession is included in Reference 3.

Recent, pertinent information on the makeup of the recreational boating industry is hard to find. The best that could be located is contained in Reference 4.

Outboard engines in-use, 1983 U.S.	9,051,000
Inboard and inboard-outboard engines in-use, 1983 U.S.	1,517,000
Recreational marine fuel use	Less than 1 percent of total gasoline consumption
Percent of recreational fuel bought at conventional automotive gas stations	85%

With respect to fuel octane needs [4] yields:

"With smaller outboard engines -- which can be roughly grouped as those below 50 horsepower -- lead-free gasoline poses few problems. For outboard engines in the 50-125 horsepower range, leaded gasoline is frequently the preferred fuel, although lead-free gasoline can often be used without adverse consequences. For outboard engines larger than 125 horsepower, an important and fast-increasing segment of the outboard population, leaded gasoline is a necessity for many designs. The same is true for the vast majority of inboard and inboard/outboard-drive engines."

Based on the cite of 9,051,000, it is evident that the total of all outboard engines in-use has increased about 146,000 per year since 1971. This is consistent with the fact that from 1961 to 1971, the total of all outboard engines in-use increased 120,000 per year[5]. The number of inboard and inboard-outboard engines has increased by about 44,000 per year since 1971.

Year	Outboards	Inboards and Inboard-Outboards	Total
1971	7,300,000	985,000	8,285,000
1983	9,051,000	1,517,000	10,568,000
1985 est.	9,343,000	1,605,000	10,948,000

From Reference 5, we also learn that recreational marine fuel use was 1.1 billion gallons in 1971. Ratioing this by the 1985/1978 population ratio yields 1.45 billion gallons per year. This is about 133 gallons per boat per year. If boats were operated about 50 hours per year on the average, this is equivalent to about 2.7 gallons per hour per boat.

For boat fuel consumption, we have assumed that 10 percent of the gasoline bought at service stations is unleaded. This value is derived from data in [1] for passenger cars. Therefore, since 85 percent of all boat fuel is purchased at gasoline stations, the number of unleaded gallons is (0.10) (0.85) (1.45 billion) 0.12 billion gallons, which is 0.1 billion to the level of accuracy needed. As an additional note, DOE's model should be debited (0.85)(1.45) = 1.2 billion gallons somewhere else for highway vehicles, to avoid double-counting when comparisons are made between model predictions and allocations of fuel used to end products.

Current information on agricultural fuel can be found in Reference 6. Much gasoline-powered equipment exists on U.S. farms, and the trend is to dieselization, rather than to equipment that uses unleaded gasoline.

DOE may well want to get a report cited in Reference 6 that we do not have. It is entitled "Outlook and Situation-Inputs," USDA, ERS IOS-4, April 1984. Some of the material used in Reference 6 and reproduced here came from that document.

	Gasoline-Fueled Equipment		
Year	Tractors	Combines	Other**
1984	1,700,000	308,000	254,000
1988	1,100,000	200,000	165,000

* Values for tractors in 1988 and others in 1984 are estimates from data in Reference 6.

** Windrowers, cotton pickers, sprayers, etc.

From the state of Indiana, one-third of farm fuel use is leaded gaoline. Also in Indiana, the farm market is 7 percent of the total market for leaded fuel[6].

In 1982, leaded gasoline accounted for 85 percent of all gasoline consumed on farms[6].

Using the above information, plus the fact that current (1985) leaded fuel consumption is 27.77 billion gallons,[1] and if we can use Indiana as a surrogate, we have:

(0.07)(27.77) = 1.94 billion gallons of leaded fuel used on farms, also

1.94/0.85 = 2.29 billion gallons of all gasoline.

Therefore, gasoline fuel consumed on farms is 2.3 billion gallons, 1.9 billion gallons leaded, and 0.4 billion gallons unleaded. This is not total farm fuel use, however, since much Diesel fuel is used.

With respect to construction equipment, [7] provides about the only data that could be located. Using the data in [7] and [1], we have computed that construction gasoline engines use 0.1 billion gallons of gasoline per year, all of it leaded, and that industrial gasoline engines consume 0.2 billion gallons of leaded gasoline per year.

Finally, [8] yields data on small engines such as those used in lawnmowers as a total of 0.1 billion gallons per year. Of this value, we assume that the unleaded/leaded split is 50-50, which puts each value almost below the tolerance level for this study.

The following table summarizes the results from Section 2.1:

Consumption Category	Fuel Consumption (billions of gals./year) Leaded	Unleaded	Total	Percent Total Purchased in Bulk
Motorcycles	0.2	0.06	0.26	0
Agricultural	1.9	0.4	2.3	50%
Marine	1.4	0.1	1.5	0%
Industrial	0.2	--	0.2	100%
Construction	0.1	--	0.1	100%
Small Engines	0.05	0.05	0.1	0%
Totals	3.85	0.61	4.46	
Percent of Total	86%	14%	100%	

Section 2.2: Leaded Fuel Needs

For the categories of fuel users listed in the summary table of Section 2.1, this section provides an estimate of the needs of each with respect to leaded fuel for valve recession protection and octane requirements. The thrust of the task here is to identify the engines possibly at risk if indeed the lead level in leaded fuel were to be lowered substantially.

Because of the scant nature of most of the data, most of what can be said about the details of the information required is more qualitative than quantitative, and, in order to make estimates of numbers of engines affected, surrogates will have to be used.

As a very rough approximation, no two-stroke cycle engines are assumed to have exhaust valve durability problems with unleaded fuel. Only octane problems exist for these engines and only for high-horsepower, high-specific power engines.

Industrial and construction engines are assumed to be like heavy-duty gasoline-fueled truck engines. In other work, EPA has assumed that 40 percent or more of these engines would operate satisfactorily with respect to valve recession on unleaded fuel.

For motorcycles, the percent of four-stroke cycle sales has been increasing. In 1983 it was 76 percent, where as in 1979 it was 66 percent[3]. Since the trend is increasing and motorcycles have a half-life of eight or so years, we can assume that 65 percent of all motorcycles on the road are equipped with four-stroke cycle engines.

This means that of the 6,960,000 total motorcycles, about 4,524,000 are equipped with four-stroke cycle engines and 2,436,000 are equipped with two-stroke cycle engines. Even though the 65 percent value is probably not constant with engine size, we have carried it along to make the computations straightforward.

Engine Size Class	Four-Stroke Cycle	Two-Stroke Cycle	Total
Under 125 cc	926,600	498,900	1,425,500
125 to 3349 cc	1,303,500	701,900	2,005,400
350 to 449 cc	504,700	271,700	776,400
450 to 749 cc	754,000	406,100	1,160,100
Over 749 cc	1,035,200	557,400	1,592,600
Total	4,524,000	2,436,000	6,960,000

With respect to valve durability, there is little or no data on engine operating characteristics for motorcycle engines and also scant published data on valve train specifics. Because of the lack of data, probably the best that can be said is that there are about 4.5 million motorcycles in-use that might have some degree of valve recession risk if unleaded fuel were used. Assuming that only the engines of 450 cc and above are the most octane sensitive than about 2.8 million motorcyles might see some octane problems if fuel octane were lowered to that typical of unleaded regular gasoline.

For outboard engines, the same sort of two-stroke cycle/four-stroke cycle and power/displacement surrogates are used to make estimates of the valve recession and octane impacts. We used the quote from [4] cited in Section 2.1.

Outboards	Octane Problem With Unleaded
Below 50 hp	No
50 to 125 hp	Half
Above 125 hp	All
Inboards and Inboard-Outboards	80 Percent

What is needed, then, is an estimate of the market breakout by horsepower for outboards. From [5] we have data typical of 1971.

Outboard Engine Power Range	Percent Engines In-Use
0 to 6.9 hp	31.5 percent
7.0 to 19.9 hp	27.2 percent
20 to 44.9 hp	27.5 percent
45 and up	18.8 percent

For the purposes of this study, we estimate that 25 percent of the engine in-use are above 50 HP, and that this is split 15 percent, 50 to 125 hp and 10 percent more than 125 hp. Of the 9,343,000 outboards engines, all are assumed to be four-stroke cycle engines.

Engine Class	Number With Potential Problems	
	Octane	Valve Recession
Outboards	1,635,000 (17%)	0 (0%)
Inboards and Inboards-Outboards	1,284,000 (80%)	1,605,000 (100%)
Total	2,919,000	1,605,000

For farm equipment, we added together the tractors and the combines as four-stroke cycle engines and assigned all the "other" category to the two-stroke cycle engine category.

With respect to the octane issue, we estimate that 25 percent of all the four-stroke cycle engines and none of the two-stroke cycle engines will have potential octane problems, and for valve recession, all the four-stroke cycle engines are counted.

Farm Equipment

Engines With Potential Problems	
Octane	Valve Recession
370,000	1,475,000

For construction equipment and industrial engines data or numbers ofengines are hard to come by.[7] We estimate that there are 500,000 construction equipment gasoline-fueled engines. Further estimates are that there are virtually all four-stroke cycle engines and that 80 percent may be subject to octane problems. As was mentioned earlier, we assume that the engines are like heavy-duty truck engines, and that 60 percent would be at risk.

	Engines With Potential Problems	
Type of Use	Octane	Valve Recession
Construction	400,000	300,000
Industrial	800,000	600,000

Small utility engines (the "lawn mower" class) are the last category. We estimate that there are 50 million such engines, and that they are split 95 percent/5 percent four-stroke cycle/two-stroke cycle, based on [8]. Not much of a problem is expected for this class on a percentage basis, in our opinion.

	Engines With Potential Problems	
Category	Octane	Valve Recession
Small engines	1,000,000	4,750,000

The following summary table should be taken with a grain of salt. This is because octane and valve recession problems are dependent on both engines design and operating conditions, neither of which have been incorporated into the study. This is why the term "potential problems" is used.

Summary Engines With Potential Problems

Type of Engine	Type of Potential Problem	
	Octane	Valve Recession
Motorcycle	2,800,000	4,500,000
Marine	2,919,000	1,605,000
Farm	370,000	1,475,000
Construction	400,000	300,000
Industrial	800,000	600,000
Small Utility	1,000,000	4,750,000
Totals	8,289,000	13,430,000

Section 2.3: Leaded Fuel Needs

This section discussed alternatives to leaded fuel which is defined as fuel with 1.1 grams per gallon lead.

In general, two things can be done to make engines compatible with a different fuel: 1) change the engine, or 2) alter the fuel. Since there are two problems under consideration, there are four topics to be discussed as indicated below.

	Fuel Fix	Engine Fix
Octane Problem	1	2
Valve Recession Problem	3	4

Fuel Fixes to Octane Problems

Two approaches can be considered: use of premium unleaded gasoline, and use of gasoline with oxygenated additives such as MTBE, TBA, ethanol, or methanol. This is a feasible solution for all the engines that may have octane problems because the assumption is made that the engines in question here are satisfied well enough on regular leaded gasoline. Drawbacks to this approach are increased cost and possible fuel system corrosion problems.

Engine Fixes to Octane Problems

It should be pointed out that the octane difference under consideration is not tremendous. Therefore, of the three engine approaches: 1) recalibration, 2) retrofit, and 3) use, recalibration is the most attractive.

A few degrees of spark retard will reseult in satisfaction for most engines with adjustable timing--the drawbacks are increased heat rejectin and increased fuel consumption. Changing to richer jets for carburetors for which this can be done may also help, but many of these engines may be running near maximum power air/fuel ratio anyway.

The way in which the engine is used can also help with octane problems. Here we are using an analogy to car operation. For some cars, owners can "drive around" octane problems. This means that they change their driving habits to avoid high knock probability modes. It may be possible to take similar measures with theengines discussed here, although the degree of successful application of this approach is not known.

Fuel Fixed to Valve Recession Problems

A very much lower level of lead than 1.1 grams per gallon is all that is needed to mitigate against valve recession, and as is well known, EPA has proposed that the value of 0.10 grams per gallon as being adequate for that purpose.

In addition to lower lead levels, other fuels additives can be used for protection against valve recession.

During the early 1970's, there were several papers that were presented that discussed fuel additives other than lead that could mitigate against valve recession. Many of these were being studied as replacements for lead if engine design changes could not solve the problem. These additives were not used in unleaded fuel because there was no need for them, not because they were ineffective as valve seat lubricants. Because there is interest now in considering what could be done as a valve protection additive package with a low or no lead, the previously published papers are of great relevance.

Douglas Godfrey and Richard Courtney of Chevron Research Company suggested some alternate compounds which could potentially be used as solid lubricants in [9]. They say that a method of preventing valve seat wear is:

> "Finding a substitute for 'lead deposits.' A high temperature solid film lubricant is needed which prevents contact and transfer. The lubricant would have to be stable to 1200°F and be noncorrosive and nonabrasive. Also, of course it must not deteriorate exhaust emission controls. Well-known high temperature solid film lubricants include, besides lead oxides, boron oxide, bismuth oxides, ceramic bonded CaF_2, and glasses. Iron phosphate from organophosphates may also serve."

Godfrey and Courtney generated no data with these compounds. Another strong indication that there are other additives that can provide as much or more protection as lead comes from Fuchs [10]. He reported three different additives that were as effective as 0.50 gplg lead in controlling valve recession. Data from his Figure 1 are reproduced below:

Additive	Minimum Concentration Needed for Effective Performance
A	250 lbs/1000 BBL
B	250 lbs/1000 BBL
C	66 lbs/1000 BBL

Fuchs did not specify the additive makeup exactly, but the paper hints that one or more of the additives contained phosphorus. It should be pointed out that the results of Fuchs were with the additives and no lead. It is expected that with 0.10 gplg lead, the performance of the additive would be as good or better, and it is possible that a different, more cost effective additive concentration (in lb/1000 BBL) could be used.

Sorem also reported encouraging results with a nonleaded fuel additive[11]. In his paper, the following statement is made:

> "With present engines, some inorganic lubricant is necessary to prevent excessive wear of the exhaust valve seat. The lead in our current fuels provides this lubrication. In the absence of lead, TCP will provide an inorganic lubricant to serve the same function."

The paper shows figures with and without a tricresylphosphate (TCP) additive that show protection of the valve seat after 100 hours of heavy-duty operation on fuel with no lead.

Kent and Finnigan[12] also investigated phosphorus additives. The following tables are reproductions of their Tables 2 and 3.

Effect of Phosphorus Dosage on Exhaust-Valve Seat Wear

Gasoline Tested	Wear in Inches			
	20 hr	40 hr	60 hr	80 hr
Base gasoline zero-lead	0.021	0.041	0.067	0.085
Base gasoline plus 0.06 gm phosphorus	0.008	0.019	0.037	0.048
Base gasoline plus 0.20 gm phosphorus	0.008	0.014	0.022	0.030

Comparative Effect of Phosphorus and Lead on Exhaust-Valve Seat Wear

Gasoline Tested	Wear in Inches			
	20 hr	40 hr	60 hr	80 hr
Commercial gasoline A, zero-lead, zero phosphorus	0.023	0.043	0.050	0.065
Commercial gasoline B, zero-lead, 0.06 gm phosphorus	0.009	0.023	0.037	0.046
Commercial gasoline C, zero-lead, 0.09 gm phosphorus	0.007	0.019	0.034	0.044
Commercial gasoline D, 0.5 gm lead	-0.001	-0.001	-0.001	-0.001

With respect to the reduction in valve seat wear afforded by the phosphorus/no-lead additive Kent and Finnigan concluded:

> "While these reductions are significant they are not sufficient to give full protection to exhaust-valve seats under high-speed operating conditions. By contrast, 0.5 gm per gallon of lead in gasoline completely protected against exhaust-valve wear under the same high-speed conditions."

Kent and Finnigan's statement can be interpreted to mean that phosphorus alone may not provide enough protection against valve seat wear.

Phosphorus was also tested by Felt and Kerley[13]. The following table is a reproduction of their Table 5.

230-CID "D" Engine,
Passenger Car Cycling Schedule*

Fuel	Lubricant	Hours	Exhaust Valve Seat Wear Rate, in./100 hr Max.	Avg.
75% alkylate + 25% toluene	**	207	0.054	0.044
Indolene + 0.05g Pb (TEL)	**	180	0.036	0.013
Indolene + 3.17 g Pb (TEL)	**	200	0.002	0.001
75% alkylate + 25% toluene	Series 3 + (M)	200	0.006	0.002
75% alkylate + 25% toluene	Comm. HD20W	107	0.106	0.082
75% A + 25% T + 0.1g phos.	Comm. HD20W	200	0.015	0.008
75% A + 25% T + 0.2g phos.	Comm. HD20W	200	0.014	0.009

* 8 hr simulated city-suburban operation-basic speed 2200 rpm (50 mph road load), 40 sec idle each 3 minutes; 4 hr freeway driving-list and 3rd at 3200 rpm (75 mph road load), 2nd and 4th cycling 3100-3400 rpm.

** Commercial ashless 10W30 oil.

Note: First four tests were run with the manufacturer's standard aluminized replacement valves. Last three tests were run with original equipment nonaluminized valves.

(M) 2.0% metal-containing additive. Oil consumption for this test was arbitrarily increased from 1800 to 500 mi/qt with wide piston ring gaps and no intake valve stem seals.

The data from Felt and Kerley indicate a substantial reduction in wear rate with 0.1 or 0.2 phosphorus, but not as large a reduction as that achieved with 3.17 gplg lead and Indolene fuel.

The effect of 0.07 gplg phosphorus in the form of cresyl diphenol phosphate was reported by Giles and Updike[14]. Figure 16 of their paper showed the effect of adding 0.07 g/gal phosphorus to Indolene clear fuel, compared to Indolene clear fuel and fuel containing 3.2 gplg lead. Results were reported for valves with 45° seats and for valves with 30° seats. The results are summarized below:

	Wear in/1000 hr			Reduction From Clear Fuel Rate	
Valve Seat Angle	Clear Fuel	0.07 phos	3.2 Pb	0.07 Phos	3.2 Pb
45°	1.53	0.87	0.37	54%	76%
30°	0.39	0.05	0.35	87%	10%

Phosphorus was better than lead for the 30° valves, but as Giles and Updike point out, 45° valve seats are the ones of greatest interest since all 1971 American-built passenger car engines used 45° exhaust seats.

Scavenger Influences

Scavengers are added to leaded fuel to reduce combustion chamber deposits. The common ones are ethylene dibromide and ethylene dichloride. These scavengers are important to valve lubricants because there is some evidence that they appear on the valve seat combined with lead.

Godfrey and Courtney[9] reported the chemical composition of valve and seat deposits. Some of the results are summarized below:

Location	Nature of the Deposit
Valve Face	$PbO.\ Pb\ SO_4$
Valve Seat	$Pb\ (CL_{0.75}\ Br_{0.25})_2$

This indicates that with engines run with conventional scavengers, the scavengers show up on the colder valve seat. Godfrey and Courtney did not report the results of any tests run without scavengers.

Cordera, et al.[15] did report some data with lead and no scavengers. Cordera, et al., found that complete removal of EDB and EDC from gasoline with 3.0 gplg lead and 0.3 theories phosphorus did not degrade valve durability on one engine. However, altering the scavenger ratio from 1.0 theories EDC and 0.5 theories EDB with 0.3 theories phosphorus to 1.5 theories EDC and 0.3 theories phosphorus (no EDB) negatively impacted exhaust valve durability on another engine. With this same engine, removal of EDC yielded mixed results--sometimes exhaust

valve life was reduced and sometimes it was nearly unchanged. Heavy-duty truck tests were run with no EDC but with some EDB and phosphorus with no negative impact on valve durability. Almost all of the data reported by Cordera were at lead levels of 3.0 gplg, however.

Engine Fixes to Valve Recession Problems

There is no simple calibration change that can take care of valve recession problems in the manner that spark advance changes solve octane problems.

Mechanical changes involve new valve seat material, typically inserts, and possibly new valves and valve guides. Another alternative is to replace the entire cylinder head with one from an engine that has been redesigned to tolerate unleaded fuel.

As in the case with octane problems, there is an engine use approach that can help protect against valve recession problems. The single most important determinant of valve recession for engines at risk is engine speed. Fits to existing data of the form in which recession rate is expressed as a constant plus RPM to some power yields valus more than 4 for the power to which (RPM/1000) must be raised.

The speed dependence means that any way the engines at risk can be slowed down will dramatically lengthen the time before valve recession progresses to unacceptable levels.

Section 2.4: Leaded and Unleaded Fuel Sales

This section describes leaded and unleaded fuel sales stratified by:

- Urban and rural;
- Geographic area;
- Wholesale (bulk) vs. retail; and
- Military and other government vs. commercial.

At the onset, it should be pointed out that this task was the one that was the most difficult to complete in a satisfactory manner.

Taking geographic area first, we have the census regions discussed in [1]. Their percent of total U.S. gasoline consumption is taken from [16].

Combining the two yields the following table which has misfueling rate by geographic area and percent of total U.S. fuel consumption by the same strata.

Census Division	Purchase Volume Rate Misfueling	Percent Total U.S. Fuel Consumption
New England	3.6	4.9
Mid-Atlantic	3.2	12.7
E. North Central	10.9	16.7
W. North Central	9.4	8.4
S. Atlantic	9.1	17.5
E. South Central	16.5	6.8
W. South Central	11.8	13.0
Mountain	11.4	5.8
Pacific	5.7	14.2

Using the total gasoline consumption for 1985 from the Eleventh Periodical Report, 92.06 billion gallons, we can calculate a matrix like those in the Eleventh Periodical Report for each census region if we make the following assumptions:

- The fraction of total fuel consumed asleaded fuel by vehicles designed for leaded fuel is the same (26.8 percent) for each region as it is nationwide; and
- The fraction of total fuel consumed as unleaded fuel by vehicles designed for leaded fuel is also a constant (3.4 percent).

When the calculations are completed, the following tables result. DOE should note that too much accuracy may be implied by these tables, and that before use by DOE some careful rounding may be necessary. The nomenclature is chosen to match the Eleventh Periodical Report.

Fuel Consumption, Billions of Gallons
Census Region: New England

Fuel Use	Design Categories Lead	Unlead	Total
Lead	1.209	0.113	1.322
Unlead	0.153	3.036	3.189
Total	1.362	3.149	4.511

Fuel Consumption, Billions of Gallons
Census Region: Mid Atlantic

Fuel Use	Design Categories Lead	Unlead	Total
Lead	4.120	1.170	5.290
Unlead	0.523	9.561	10.084
Total	4.643	10.731	15.374

Fuel Consumption, Billions of Gallons
Census Region: W. North Central

Fuel Use	Design Categories Lead	Unlead	Total
Lead	2.072	0.507	2.579
Unlead	0.263	4.891	5.154
Total	2.335	5.398	7.733

Fuel Consumption, Billions of Gallons
Census Region: S. Atlantic

Fuel Use	Design Categories Lead	Unlead	Total
Lead	4.318	1.023	5.341
Unlead	0.548	10.222	10.770
Total	4.866	11.245	16.111

Fuel Consumption, Billions of Gallons
Census Region: E. South Central

Fuel Use	Design Categories Lead	Unlead	Total
Lead	1.678	0.721	2.399
Unlead	0.213	3.648	3.861
Total	1.891	4.369	6.260

Fuel Consumption, Billions of Gallons
Census Region: W. South Central

Fuel Use	Design Categories Lead	Unlead	Total
Lead	3.207	0.986	4.193
Unlead	0.407	7.368	7.775
Total	3.614	8.354	11.968

Fuel Consumption, Billions of Gallons
Census Region: Mountain

Fuel Use	Design Categories Lead	Unlead	Total
Lead	1.431	0.425	1.856
Unlead	0.182	3.301	3.483
Total	1.613	3.726	5.339

Fuel Consumption, Billions of Gallons
Census Region: Pacific

Fuel Use	Design Categories Lead	Unlead	Total
Lead	3.503	0.520	4.023
Unlead	0.444	8.606	9.050
Total	3.947	9.126	13.073

For each of the census regions, the percent of the population that is included within Standard Statistical Metropolitan areas (SSMAs) is known. From these values we can compute gasoline volume matrix for each census region, disaggregated by SSMA-non SSMA.

The values from [17] are shown below:

Census Division	Percent of Population Within SSMAs
New England	76.6
Mid-Atlantic	87.7
E. North Central	78.1
W. North Central	53.3
S. Atlantic	70.5
E. South Central	51.9
W. South Central	70.4
Mountain	63.1
Pacific	89.4

Applying these values to each of the disaggregated estimates provided earlier, one can reaggregate to the national level by SSMA/non-SSMA.

Fuel Consumption,
Billions of Gallons, SSMA Areas

Fuel Use	Design Categories Lead	Unlead	Total
Lead	18.204	4.022	22.226
Unlead	2.310	43.392	45.702
Total	20.514	47.414	67.928

Fuel Consumption,
Billions of Gallons, Non-SSMA Areas

Fuel Use	Design Categories Lead	Unlead	Total
Lead	6.467	1.704	8.171
Unlead	0.821	15.231	16.052
Total	7.288	16.935	24.223

The above total fuel consumption is close to the total cited earlier, 92.15 vs. 92.06 due to rounding, but the difference is not considered important. Note that 74 percent of the fuel used is used in SSMA areas, compared to 75 percent of the populationo, even though state-by-state gallons were used to compute the result. Therefore, the overall rural/urban fuel consumption relationship matches the population closely. This analysis also corroborates that shown in [2] in that estimates for the urban misfueling gallon ratio (4.022/47.414), 8.5 percent is lower than for the non-urban misfueling gallon ratio (1.784/16.935), 10.1 percent.

In addition to urban/rural and geographic regions, the Statement-of-Work requests breakdown by wholesale (bulk) versus retail sales, and military and governmental sales.

In [18], we can locate some information on bulk sales if the following assumptions can be made:

1. All premium is unleaded;

2. All refiner sales "to end users" are bulk; and

3. All refiner sales "for resale" are not bulk.

Data for August, 1984 are shown below in millions of gallons:

Gasoline Type	Sales		
	To End Users	For Resale	Total
Leaded Regular	641	3,539	4,180
Unleaded Regular	915	3,636	4,551
Premium	285	1,137	1,422
Total	1,841	8,312	10,153

Overall, 18 percent of sales were to end users. For leaded regular the value is 15 percent, for unleaded regular the value is 20 percent, and for "premium" it is also 20 percent. Therefore, the value for unleaded fuel is somewhat higher at about 20 percent than it is for leaded fuel, based on Table 1 of [Z]. As an aside, Table 1 of [18] allows us to estimate that 0.4 billion gallons per year of gasoline is consumed as finished aviation gasoline.

However, the previous data does not separate out gasoline sold in retail outlets. Accounting for this the percent of sales is a gallon basis, that value drops to 3.1 percent of gasoline sales (Table 33), but a distinction among the types of gasoline is not made.

Taking data from [18] and the consumption tables look like those below with the values all backsolved from 3.1 percent total, and a 0.75/1.0 ratio of leaded to unleaded bulk sales. Furthermore, no fuel switching is assumed to occur, and to put the best light on the use expected from this analysis, misfueling is also assumed to be zero. Retail sales are obtained by the difference.

From [1] for 1985:

Highway Vehicles,
Billions of Gallons

Fuel Use	Design Categories Lead	Unlead	Total
Lead	24.68	5.63	30.31
Unlead	3.09	58.66	61.75
Total	27.77	64.29	92.06

Bulk Sales,
Billions of Gallons

Fuel Use	Design Categories Lead	Unlead	Total
Lead	0.754	0.000	0.754
Unlead	0.000	2.100	2.100
Total	0.754	2.100	2.854

Retail Sales,
Billions of Gallons

Fuel Use	Design Categories Lead	Unlead	Total
Lead	23.926	5.630	29.556
Unlead	3.090	56.560	59.650
Total	27.016	62.190	89.206

For military and other governmental sales, no data beyond what DOE already has could be found. The documents are the "Federal Motor Vehicle Fleet Report" and the "Defense Fuel Supply later Fact Book." DOE can use these, but we were unable to determine how much overlap there is between the two sources.

References

1. "The Motor Fuel Consumption Model - Eleventh Periodical Report," Energy and Environmental Analysis, Inc., under Work Assignment No. 8 of Contract No. 68-03-1865, November 7, 1984.

2. "Patterns of Vehicle Misfueling in 1981 and 1982: Where, When, What Vehicles and How Often?" SAE Paper No. 841345, B. O. McNutt and D. Eliot, October, 1984.

3. 1984 Motorcycle Statistical Annual, published by the Motorcycle Industry Council, Inc.

4. Statement of Richard H. Lincoln, Member, Board of Directors, National Marine Manufacturers Association, before the Committee on Environment and Public Works of the United states Senate in Opposition to S.2609, June 22, 1984.

5. "Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines, Part 2: Outboard Motors," C. T. Hare and K. J. Springer, Final Report, Contract No. EHS70-108, January, 1973.

6. Testimony of R. Thomas Van Arsdall, National Council of Farmer Cooperatives, Before the Senate Environment and Public Works Committee, In the matter of S.2609 "Airborne Lead Reduction Act of 1984," Friday, June 22, 1984.

7. "Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines, Part 5: Heavy Duty Farm Construction and Industrial Engines," C. T. Hare and K. J. Springer, Final Report, Contract No. EHS70-108, October, 1973.

8. "Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines, Part 4: Small Air-Cooled Utility Engines," C. T. Hare and K. J. Springer, Final Report, Contract No. EHS70-108, May, 1973.

9. "Investigation of the Mechanism of Exhaust Valve Seat Wear in Engines Run on Unleaded Gasoline," SAE Paper No. 710356.

10. "Unleaded Versus Leaded Fuel Results in Laboratory Engine Tests," SAE Paper No. 710676, by E.J. Fuchs of the Lubrizol Corporation.

11. "Effects of Fuel Factors on Emissions," SAE Paper No. 710364, by S. S. Sorem of Shell Development Corporation.

12. "The Effect of Some Fuel and Operating Parameters on Exhaust Valve Seat Wear," SAE Paper No. 710673, by W. L. Kent and F. T. Finnigan of the Union Oil Company of California.

References (cont'd)

13. "Engines and Effects of Lead-Free Gasoline," SAE Paper No. 710367 by A. E. Felt and R. V. Kerley of Ethyl Corporation.

14. "Influence of Low Lead Fuels on Exhaust Valve Performance," SAE Paper No. 710674, by W. S. Giles and S. H. Updike of the Valve Division, TRW Incorporated.

15. "TEL Scavengers in Fuel Affect Engine Performance and Durability," SAE Paper No. 877A, by F. J. Cordera, H. J. Foster, B. M. Henderson, and R. L. Woodruff of Shell Oil Company, June, 1964.

16. "Highway Statistics," U.S. Department of Transportation, Table MF21A, 1983, p. 6.

17. State and Metropolitan Area Data Book, A Statistical Abstract Supplement, U.S. Department of Commerce Bureau of the Census, 1982, p. 450.

18. Petroleum Marketing Monthly, E/A DOE/EIA-0380(84/08, November, 1984.